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Medical Devices for Measuring Respiratory Rate in Children: a Review

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Abstracts: Respiratory rate is an important vital sign used for diagnosing illnesses in children as well as prioritising patient care. All children presenting acutely to hospital should have a respiratory rate measured as part of their initial and ongoing assessment. However measuring the respiratory rate remains a subjective assessment and in children can be liable to measurement error especially if the child is uncooperative. Devices to measure respiratory rate exist but many provide only an estimate of respiratory rate due to the associated methodological complexities. Some devices are used within the intensive care, post-operative or more specialised investigatory settings none however have made their way into the everyday clinical setting. A non-contact device may be better tolerated in children and not cause undue stress distorting the measurement. Further validation and adaption to the acute clinical setting is needed before such devices can supersede current methods.

Keywords: Respiratory rate, Monitoring, Measurement, Children, Medical devices.

INTRODUCTION

The measurement of a child's vital signs including heart rate, temperature, blood pressure and respiratory rate is routine practice to all those who attend emergency departments and Paediatric assessment units. Respiratory rate is an important vital sign and is used in the initial and ongoing assessment of unwell children [1]. It can be used to assess a child's clinical status and as a predictor of serious deterioration [2].

Respiratory rate is one of the few signs that rely on clinical observation and not electronic conformation, and in children it can be particularly challenging to measure. The child may be uncooperative, unsettled or crying, meaning it is harder to observe their breathing movements and make an accurate count. A medical device to measure respiratory rate may help overcome these difficulties.

Many electronic devices to measure respiratory rate exist however none are in use within the triage and everyday clinical setting. These devices use multiple different methods to ascertain the respiratory rate of a subject and can be divided into contact and non-contact methods [3]. This review article aims to evaluate devices that could be used in children to

measure respiratory rate, both contact and non-contact methods, and their suitability to enter clinical practice.

Contact Based Respiratory Rate Monitoring

Contact respiratory rate (RR) monitors make direct contact with the patient's body and make use of a number of different methods to obtain a respiratory rate. These include measuring chest and abdominal movements, acoustic sounds and airflow, exhaled carbon dioxide and calculating the RR from the electrocardiogram (ECG) or oxygen saturation. The main disadvantage of such contact methods is that in children they may be less well tolerated, potentially causing stress to the child altering their respiratory rate.

Movement Detection

By placing bands around the subject's chest and abdominal wall, measurements of the thoracic impedance changes associated with respiration can be measured [4]. This method provides continuous measurements in a controlled environment and is established in the monitoring of sleep disorders in infants and children and is the method recommended by the Royal College of Paediatrics and Child Health [5]. However, this method has had mixed results when applied to adults in the acute setting [6, 7]. Also its application to the Paediatric population may be difficult due to the time taken to set up and the contact bands may not be well tolerated in younger children.

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Airflow Methods

Various methods that detect airflow can be used to measure respiratory rate. These include using thermistors placed in the nose of the patient to detect changes in air temperature [8], nasal pressure transducers to measure the volume of exhaled air [3] and sensors detecting expired carbon dioxide (capnometry) [9]. These methods are used primarily in controlled environments and in the post-operative setting. Although potentially accurate, they require sensitive equipment to be attached to the subject. This may not be well tolerated in children and as these devices can only be used once per patient there may be large cost implications if they are being used for one off RR measurements in an acute clinical setting.

Acoustic Methods

Acoustic methods analyse respiratory vibrations to detect inspiratory and expiratory flow. The acoustic signal is then converted to a respiration rate. This method can provide an accurate measurement of RR and also monitor for apnoeas [10-13]. One study conducted in post-operative children showed the acoustic method (Rainbow acoustic monitoring - RRATM) had a good agreement and a similar accuracy when compared to capnography [12]. This method is not affected by subjects breathing through their mouth or nose and appears to be well tolerated by patients in the post-operative setting. However swallowing, coughing, speaking and large amounts of background noise can lead to inaccuracies in these measurements.

Electrocardiogram Derived Measurement

This method relies on attaching ECG electrodes to the subject and measuring the fluctuation associated with respiration to derive a respiratory rate. This is known as ECG derived respiration (EDR) [14]. This method has now been reported using a single-channel ECG [15] and can detect obstructive apnoea and changes in tidal volume [16]. However it still appears less accurate when compared to airflow and movement methods of RR measurement [17].

A further development on this method is a small wireless patch sensor from Vital Connect [18]. The HealthPatch MD consists of two ECG electrodes, a tri-axial accelerometer, micro-controller, and transceiver within a patch that straps like a bandage over the heart. The device measures heart rate, respiratory rate, steps and posture and connects wirelessly to a smartphone via bluetooth.

Respiratory rate is calculated by combining information from the ECG derived respiratory signal as well as chest movement signals from the accelerometer. The device has been given FDA approval but has only been tested on 25 healthy adults against RR data from capnography. The mean absolute error between respiratory rates was 1.0 ± 0.1 breaths/min, however it is difficult to draw any statistical conclusions from this data [19]. Although in its early phase this device offers the potential for long-term remote monitoring of RR, no testing on children has taken place to validate the device in this population.

Another similar device, the Orient speck [20], has also been developed which acts in a similar way to the HealthPatch MD. It is wireless patch worn on the torso of a subject and through an integrated tri-axial accelerometer is able to detect respiratory rate movements and derive a respiratory rate. Information is stored on the device and will download wirelessly when it is within range of a base-station. The device has been tested clinically on 19 post-operative adult patients [21]. When compared with a nasal cannula pressure monitoring device the RR from the Orient speck matched within 2 breaths/min on 86% of occasions.

These devices offer the potential of monitoring RR remotely and continuously. However, as with the other contact methods they may cause distress to a small child due to their contact with the chest. They also do not currently appear appropriate for use in the accident and emergency triage setting but more as an option for longer term remote monitoring. The cost of applying a single use patch to each patient presenting acutely may not be feasible and the time delay in obtaining a reading may be significant.

Respiratory Rate from Photoplethysmography

Photoplethysmography (PPG) utilises a monitoring system that is already widely used in measuring patient's oxygen saturation levels. Leonard *et al.* [22] described using pulse oximeters in 10 healthy adults to extract respiratory waveforms to determine respiratory rates. This method has also been widely tested in newborn infants [23-25]. Olson *et al.* reported a high degree of association between PPG and thoracic impedance measurements in 10 newborn infants ($r = 0.99$) [24]. Wertheim *et al.* have shown they were able to reliably monitor respiratory rates from a commercially available pulse oximeter in term and preterm infants [25, 26]. This method has also been extended into children with preschool wheeze [27]. 18 acutely wheezy children had their RR derived from

pulse oximetry plethysmogram and compared against clinical assessment. The plethysmogram analysis was within 10 breaths/min of the clinical assessment during the acute episode. Clearly the accuracy of this method would need to be improved before it could be considered as an acceptable alternative for measuring respiratory rate in the acute setting.

Table 1 summarises the various contact methods available for measuring respiratory rate.

Non-contact Based Respiratory Rate Monitoring

With non-contact respiratory rate monitors the device does not make contact with the patient's body. This method may be more suitable in the acute setting and also in children, where a contact method may not be tolerated and also unintentionally alter the respiratory rate.

Infrared Thermography

Infrared thermography can be used to monitor fluctuations in facial skin surface temperature using an infrared detection device. During exhalation the skin temperature on the tip of the nose increases and a respiratory signal and rate can be extracted [28]. Abbas *et al.* [29] were able to detect respiration in preterm infants on a neonatal unit based on a 0.3-0.5 °C temperature difference between inspiration and expiration. This technique has also been demonstrated to work well in resting children, and when compared with conventional contact methods a close correlation was seen (correlation coefficient = 0.994) [30]. However this technique requires complex equipment and detailed calibration to set up, and in its current form would not be a viable option to be used in everyday clinical practice.

Table 1: Contact Methods of Measuring Respiratory Rate

Method	Mechanism	Application Areas	Advantages	Disadvantages
Movement detection	Mercury strain gauge or impedance methods detect chest and abdominal wall movements through bands placed around subject.	-Sleep studies.	-Continuous accurate measurements. -Can detect subtle thoraco-abdominal asynchrony related to specific respiratory disorders.	-May not be well tolerated by younger children. -Can be subject to motion artefact.
Airflow measurements	Air temperature, pressure and CO ₂ measurement of exhaled air.	-Post-operative setting.	-Potentially very accurate method of monitoring RR. -Provides a continuous method of monitoring.	-Expensive equipment. -Probe has to be positioned in the exhaled airflow. Can be easily dislodged and may not be well tolerated in children.
Acoustic Method	Analyses respiratory vibrations to detect inspiratory and expiratory flow. The acoustic signal is converted to a respiration rate.	-Controlled environments. -Post-operative setting.	-Good accuracy when compared to capnography. -Better tolerated than other contact methods in post-operative subjects. -Not affected by mode of breathing.	-Few studies in children. All on post-operative patients. -May not be well tolerated by the awake or agitated child. -Reading altered by swallowing and other noises. The child would have to be silent.
Respiratory rate derived from electrocardiogram	Small morphological changes occur on the ECG during respiration. From these the respiration rate can be derived.	-Intensive care setting. -Remote monitoring of patients in community.	-Low cost alternative when ECG monitoring already in use. -Avoids high frequency currents and frequent recalibration. -Small patch devices now in development.	-Readings often disrupted by motion artefact. -Lacking in accuracy when compared with more established contact methods.
Respiratory rate derived from photoplethysmography (PPG)	Pulse oximeter is based on PPG where red and infrared frequencies detect blood oxygen saturation level. RR can be monitored by looking at respiratory induced intensity variations contained within the PPG signal.	-Intensive care setting. -Post-operative setting. -Sleep studies. -Triage setting along with O ₂ saturations.	-Small probe size which may be better tolerated especially in infants and children. -Allows for continuous monitoring.	-Motion disturbances can lead to inaccuracies in measurements. -Risk of autonomic nerve activity influencing PPG signal.

Video Data

Video images have also been shown to provide RR measurements. The differences between video frames can be used to estimate movements and provide a RR [31]. Alternatively a RR and heart rate (HR) can be derived from analysing the video for skin colour changes observed in a subjects face [32]. These techniques may provide an accurate measurement of respiratory rate but require good illumination of the face and are not appropriate for sleep monitoring.

Aoki *et al.* [33] projected infrared light spots onto subject's chests and used cameras to determine the distance these light spots moved with respiration to derive a RR. Whilst this method could be used in the sleep study setting the projected light spots can be distracting for children. Also large movements and different sleeping positions affect the accuracy of this method. A further development of this by Koolen *et al.* 2015 [31] used a Eulerian video magnification to amplify respiratory movements. They used this to analyse the RR in 7 neonates, including those in dark settings, and were able to detect the RR on 94% of occasions. Further validation of this method is required, however it does offer a cheaper simpler alternative that could be trialled in the triage and ward setting.

Humidity Detection

This method is based on the measurement of the humidity of exhaled air, which is then converted to a respiratory rate reading. Niesters *et al.* [34] have utilised this method by placing such a device within a facemask. They validated this in 28 healthy adults and found close agreement when compared with capnometry and the standard visual counting method (limits of agreement ± 1 breath/min). Their method of measurement may be of use in the post-operative setting however it requires further testing and validation in children and other clinical settings before it can be adopted more widely.

Ultrasound

Ultrasound has been used to measure respiratory rate in a number of different ways [35, 36]. Firstly by ultrasound wave telemeters that detect small body movements associated with respiration [35]. More recently Arlotto *et al.* have developed an ultrasonic contactless sensor that measures the frequency shift produced by the velocity difference between the exhaled air flow and the ambient environment to derive a RR [36]. This method is yet to be validated in the clinical setting and measurements

appear to be effected by movement of the subject. However it may have applications in continuous RR monitoring in neonates and infants in an intensive care environment and also in the diagnosis of sleep apnoea.

Radar

Radar methods offer another option for the contactless measuring of RR. Grenaker first utilised this method in monitoring the performance of Olympic athletes from distances over 10 meters [37]. More recently Droitcour *et al.* [38] developed a low powered Doppler radar system and compared measurements of RR in 24 hospitalised adults against a standard contact method. The 95% limits of agreement fell within -4.5 and 1.8 breaths/min. This method has also been extended for use in babies. By using continuous wave Doppler radars Hefner *et al.* [39] were able to measure the RR of preterm infants on a neonatal intensive care unit. However, these options remain complex to set up and potentially costly and at present may not offer a better alternative to current monitoring methods.

Mobile Applications

Mobile applications provide a portable way of measuring RR. Philips vital sign mobile application measures both heart rate and respiratory rate using the built-in camera on a mobile device [40]. By detecting facial flushing with each heart beat and chest movement, an estimation of HR and RR is given. The device has not been clinically tested and caution must be taken in bringing such an application into the clinical setting before it has been rigorously tested and validated.

Karlen *et al.* have produced another mobile application to measure RR [41]. The *RRate* mobile application estimates the RR of the subject by measuring the median time interval between breaths obtained from tapping on the touch screen of a mobile device. They obtained data from 30 subjects estimating the RR from 10 standard videos. They observed that the efficiency (time to complete a RR measurement) was improved by using this device, however by increasing the efficiency of the measurement accuracy was lost. They suggested the most balanced optimisation resulted in the measurement taking 9.9 seconds to complete, which corresponded to an error of 2.2 breaths/min at a RR of 40 breaths/min.

This application again needs further testing within a clinical setting, and on subjects of different ages. Although it does offer a potential improvement in the

Table 2: Non-Contact Methods of Respiratory Rate Measurement

Method	Mechanism	Application Areas	Advantages	Disadvantages
Infrared thermography	Detects fluctuations in skin surface temperature created by exhaled air and converts this to a respiratory signal.	-Neonatal intensive care setting. -Sleep study setting.	-Extremely accurate method, comparable to available contact methods. -Useful application in a sleep study setting.	-Long processing time to convert images and derive a RR. -Difficulties when subjects breath through both nose and mouth. -Head movements cause large inaccuracies. -Complex expensive equipment with long set up times.
Video data	RR derived through analysing video data. By detecting movement changes of subject, or infrared light spots, magnification of movements, or changes in skin colour.	-Intensive care environment. -Neonatal intensive care. -Triage and ward setting.	-Simple cameras using standard resolution images can be used. -Some methods are easy to use, and could be used in ward or home environment.	-Some cameras will not work in poor light. -Measurement may be inaccurate if subject makes large or frequent movements.
Humidity detection	Device quantifies humidity of exhaled air. Derived signal is transmitted to monitor that calculates RR breath-by-breath.	-Post operative setting. -Intensive care.	-Provides continuous RR data useful in post operative or intensive care setting. -Small, mobile device.	-Device placed inside face mask, will not work unless subjects wear face mask. -Readings affected by low expiratory flow rates and water condensation.
Ultrasound	Can detect small body movements in respiration. Can also utilise doppler effect to detect velocity difference in exhaled air and environment.	-Sleep study setting. -Intensive care setting.	-Easier detection of sleep apnoea. -May be well suited for continuous monitoring in preterm infants.	-Inaccuracies with movement or if subject has nasal cannula in situ. -Potentially expensive and difficult to set up.
Radar	Detects breathing movements of the chest using the doppler phenomenon.	-Sleep study setting. -Intensive care setting.	-Can be used at long distances. -Possibility of wireless transfer of RR data to central unit.	-Movement creates artefact which alters RR signal. -Currently expensive and difficult to set up.
Mobile phone applications	1.Detection of chest movement through mobile phone camera (Philips Vital Sign).		-Portable, quick and easy to use. -Very user friendly.	-Not yet validated clinically. -Measurements may be very inaccurate.
	2.RR derived from mean time interval between breaths by tapping on mobile device (RRate).		-Portable, easy to use and reduces time taken to measure RR. -Could be used in resource limited settings.	-Still requires subjective assessment of RR. -Time of measurement may effect accuracy.

efficiency of measuring RR, the application still relies upon a subjective assessment which could lead to further inaccuracies.

Table 2 summarises the non-contact methods of respiratory rate measurement.

CONCLUSION

The measurement of respiratory rate in children can be challenging. Although devices for measuring respiratory rate exist, none have entered everyday

clinical practice for the acute assessment of children. Many devices require body contact, which may not be practical and could be distressing to the child, inadvertently altering their RR. Other devices are limited by cost and methodological complexities. A non-contact device seems to be preferable in children as it may be better tolerated and not cause undue stress to the child. However further validation, improvement in accuracy and adaption to use in the clinical setting is needed before these devices supersede current methods of measurement.

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